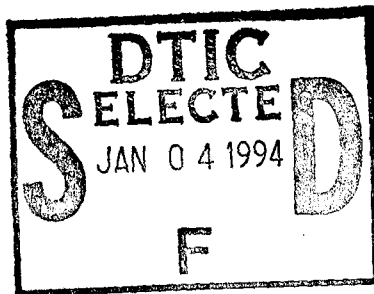


Demonstration Study of Hierarchical Control
of
Fluid-Dynamic Phenomena

(Office of Naval Research Grant No. N00014-89-J-3018)

-Final Report-



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1 Abstract

This document is a final report for ONR grant N00014-89-J-3018, "Demonstration Study of Hierarchical Control of Fluid-Dynamic Phenomena." Our overall objective was to develop a laboratory experiment wherein the performance of a fluid dynamic process would be effectively controlled using a model-based system controller. We considered, as a sample fluid-dynamic process, the flow over a high-lift circulation-control wing. The essence of our model-based approach was a progression of fluid-dynamic models corresponding to the expected range of complexity in the attached and separated flow of the experiment. Development of the demonstration involved both fabrication and testing of the high-lift wing model and test apparatus, as well as coding and evaluation of the control algorithms and fluid-dynamic models. Preparatory to this development, a flow facility in which to conduct the experiments had to be designed and constructed. Unfortunately, due to delays in completion of this facility, the demonstration experiments could not be carried out within the budget of the grant. Our overall objective was therefore not met, however, we will report here on the substantial progress we did make to establish the capabilities cited above.

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2 Introduction

The overall objective of this ONR grant (N00014-89-J-3018), "Demonstration Study of Hierarchical Control of Fluid-Dynamic Phenomena," was to apply a model-based control approach to demonstrate enhanced performance in a sample fluid-dynamic process. Our motivation was to utilize existing technologies in the fields of fluid mechanics and control theory to achieve this objective. This interdisciplinary approach involved cooperation between the Aero. & Fluid Dynamics (AFD) laboratory and the Estimation and Control Laboratory (ECL), both in the Mechanical Engineering Department.

Completion of our objective involved three primary phases, as indicated in Figure 1 below. These tasks correspond to a three-year period as discussed in the proposal Statement of Work.

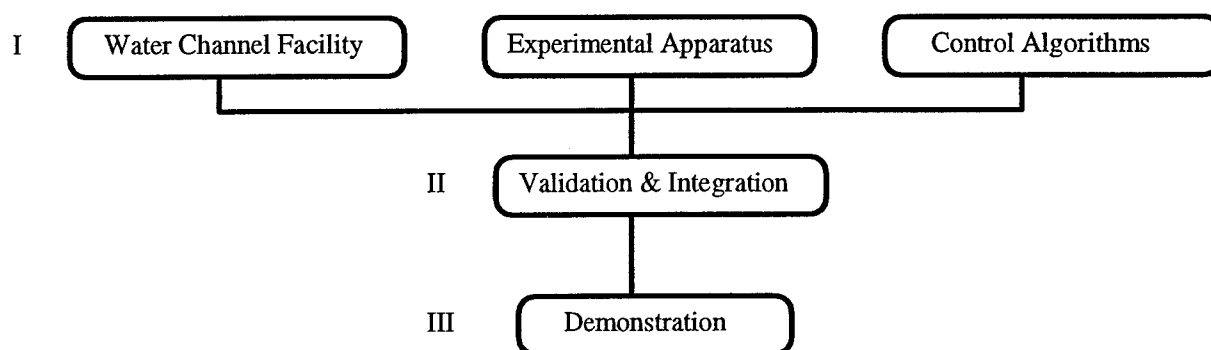


Figure 1: Project Phases

During Phase I, significant delays were encountered in the design and construction of the water channel facility. For this reason a no-cost extension was granted to extend the contract period to September 1992. Due to the above delays however, Phases II and III of the project could not be completed. We will therefore focus here on our accomplishments in Phases I and II, including development of the facilities, the experimental apparatus, and development and implementation of the flow-field models and control algorithms.

2.1 Facilities and Experimental Apparatus

Many valuable developments in the AFD Laboratory occurred through this ONR funding, and through other funds related to it. Under this grant, ONR funds for facility and equipment totaled \$80,000. A College of Engineering matching fund of \$20,000 was committed initially, but matching funds exceeded this amount, finally reaching a level of 50% matching to the ONR facility/equipment funds. At initiation of this grant, the college also redirected some renovation funds to the AFD laboratory area. Improvements to the laboratory lighting were made and the Control Room was constructed. Also, other research funding from Sandia National Laboratory (SNL) was complementary to this effort. In the Masters Project of Meier [1], a load balance was designed under SNL funding. Two of

these balances were machined without charge by the NMSU Manufacturing Teaching Facility (MTF). Additional machined items were donated to the ONR/SNL activities by our manufacturing center, including numerous traversing mechanism and wing model components.

The primary AFD laboratory developments are discussed in more detail in Section 3, AFD Laboratory Development. Foremost of these is the Low Turbulence Water Channel (LTWC) facility. Our objectives in designing this facility included: 1) suitability for unsteady aerodynamics studies, 2) large test section with good optical accessibility, 3) ample stilling chamber for superior flow conditioning, 4) low maintenance. The LTWC facility is currently operational, providing flowrates from $U = 0.3$ ft/sec to $U = 1.5$ ft/sec. Flow quality will not be up to standards until the flow conditioning (honeycomb and screens) can be acquired and installed.

A range of experimental capabilities are also now available in the AFD laboratory. General capabilities include a Data Acquisition and Control System (DACS), signal conditioning, computer controlled servo-driven model traversing, twin 3-component load balances, and flow visualization. An elliptical circulation control wing was fabricated for the demonstration experiments. This model configuration was chosen because of the availability of the experimental data of Kind & Maull [2]. Some machining problems were encountered with this model, so it is not completed. A servo-controlled injection system was developed for the wing model, and this system is operational.

A description of each of these capabilities is given in Section (3). Complete details of these capabilities and their development can found in the senior project reports [3, 4, 5].

2.2 Control Algorithms

Flow-field models to be employed in the model-based compensator are completed, and are documented in the MS thesis of Curtis Ober [6]. The models range in complexity from a simple empirical look-up table relating the lift coefficient to angle-of-attack and blowing coefficient, to a panel/integral boundary-layer method for predicting lift, circulation, and separation. Mr. Ober also completed development of an O-grid finite difference model for the potential flow problem. An extension to this work, not funded by ONR, is described in the PhD thesis of Nabil Karabash [7]. Here the unsteady inviscid case is considered by implementing a parallelized finite difference Warming and Beam algorithm on a Los Alamos National Laboratory CM-2 machine.

Development of the system controller and implementation of the flow-field models are addressed in the MS thesis of Lt. Robert Robledo [8], U.S. Navy. Lt. Robledo was an Engineering Duty Officer while at NMSU. Two subsystems were considered, for injection control and angle-of-attack control. The injection subsystem controller is complete and operational. The angle-of-attack subsystem was not completed, due to some delays in development of the software device driver for the servo motor. These developments are described in Section (4).

3 AFD Laboratory Development

The Aero. & Fluid Dynamics (AFD) Laboratory is a 2,400 sq-ft laboratory in the Mechanical Engineering Department. This laboratory was established in 1990, and now houses the Low Turbulence Water Channel (LTWC) facility, the AFD Control Room, and a range of laboratory instrumentation and support equipment. Target research areas for the laboratory include topics in unsteady aerodynamics and associated fluid mechanics problems. The AFD laboratory was developed primarily through ONR grant support, the subject of this final report. Additional funds from Sandia National Laboratory have supported some of the equipment development described here. The following sections describe what laboratory capabilities were developed.

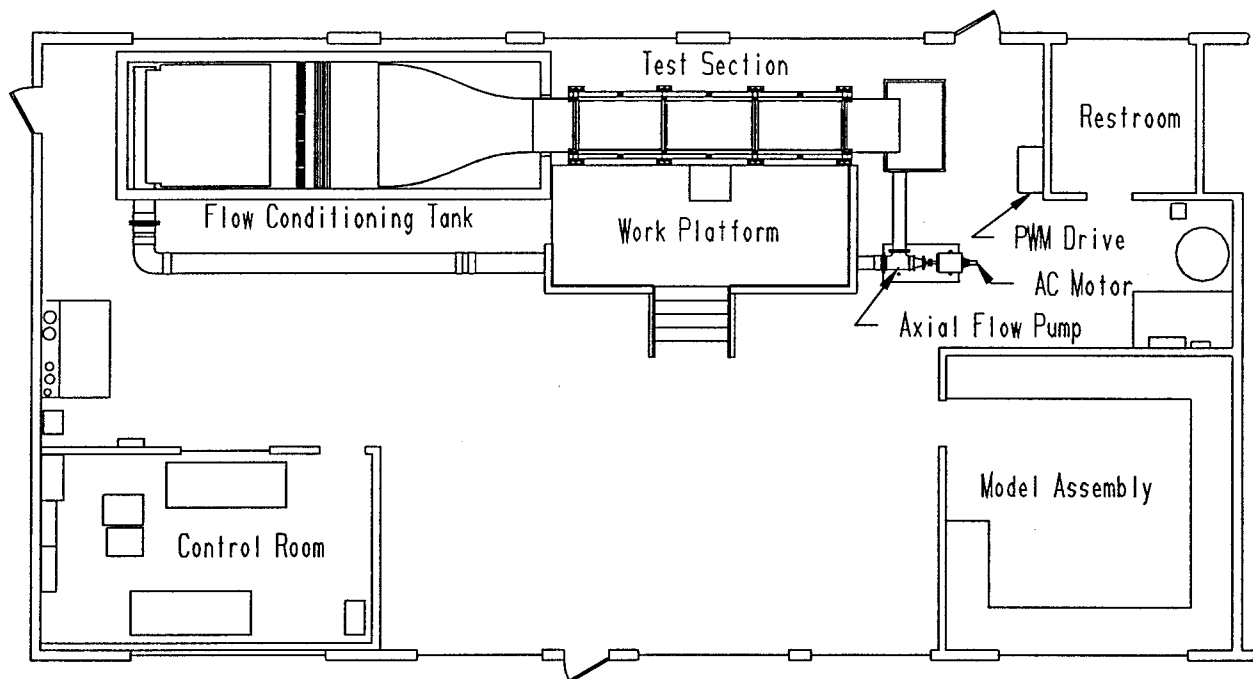


Figure 2: AFD Laboratory

3.1 LTWC Facility

The most significant capability in the AFD laboratory is the LTWC facility. This is a large recirculating-flow open-surface water channel, designed to provide a uniform and low-turbulence flow. Particular efforts were taken to attain low vibration, and to maintain a clean flow field environment in the facility. Because of the possibility of component corrosion in water, and associated flow contamination; corroding materials were held to a minimum. In size, the LTWC facility is 55 ft in overall length, and a capacity of 16,000 gallons of water, Figure 3.

The LTWC facility provides an ideal environment for detailed qualitative and quantitative

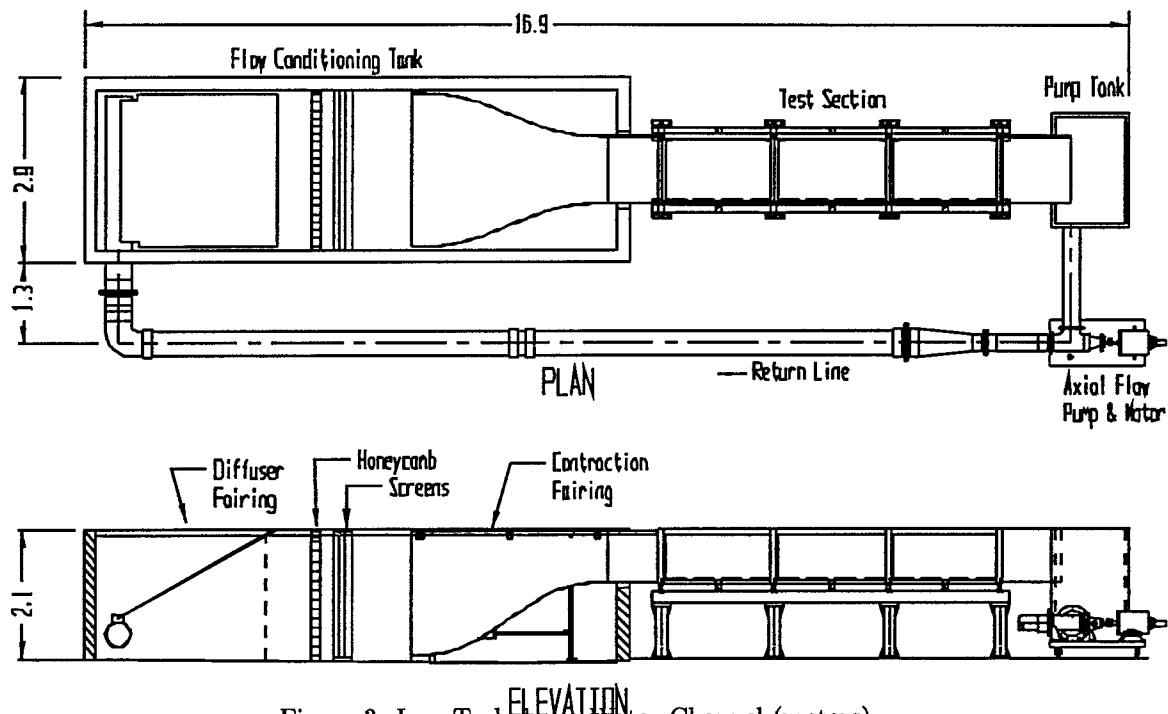


Figure 3: Low Turbulence Water Channel (meters)

flow field evaluation. At low Reynolds number, the facility is a valuable resource for evaluation of numerical flow-field models, particularly when unsteady effects are important. Dimensional scaling is particularly advantageous in the case of flow field unsteadiness. For evaluation of oscillatory or transient phenomena, the convective time, $\tau = L/U$, in the LTWC can be 2-3 orders of magnitude longer than for typical wind-tunnel conditions. Also, the acceleration number, $A = a\tau/U$, corresponding to a prototype acceleration of 30 times gravity, can be attained with a model acceleration in the LTWC of $a_m = 0.25 \text{ ft/sec}^2$. This acceleration is well within the capability of the existing traversing mechanism servo drive.

In addition, the LTWC is ideally suited to application of non-intrusive optical velocimetry techniques which rely on use of seeding particles. The flow tracking dynamics of these particles is more favorable in a low-speed water flow than in air, and a recirculating flow is needed to maintain necessary seeding densities. The primary components of the LTWC facility are described below.

3.1.1 Reinforced Concrete Components

Prior to construction of the channel itself, extensive demolition was carried out to remove the existing concrete floor slab. This was replaced by a 6 inch reinforced high-strength concrete slab, supported by engineered fill. Isolation pads were constructed for the pumping system and for the test-section supports. The flow conditioning tank was also constructed of high-strength reinforced concrete. This long-walled water retention tank is

30 ft long, 8 ft wide, and has 8- inch thick walls and floor. The concrete design for the tank was based on a finite-element stress analysis in conjunction with criteria for ultimate strength and for curing-crack resistance. The curing-crack criteria was most stringent, and was therefore utilized to maintain a leak resistant structure. The concrete design for this tank is described in the report of Travis [9].

Interior surfaces of the flow conditioning tank are epoxy sealed. Thus, a highly corrosion resistant structure contains the flow-conditioning components, described below. These relatively light weight modular components are easily installed, can be accurately aligned in the facility. They may also be removed from the LTWC facility for maintenance in the AFD area if necessary.

3.1.2 Flow Conditioning Components

Flow conditioning components include the diffuser fairing, the honeycomb and screens, and the contraction fairing. The contraction fairing is constructed of wood & epoxy-resin composite. It provides a area contraction ratio of 5.4:1, with wall and floor contours following a fifth-degree polynomial. The corresponding contraction-to-length aspect ratios are, 0.19:1 for each wall, and 0.37:1 for the floor. The contraction fairing is complete and installed. Its design is described in the Senior Design Project report of Miller et. al. [10].

The remaining flow conditioning devices are not complete. A 1-D flat diffuser must be fabricated and installed in the conditioning tank. Funds are currently lacking for procurement and installation of the honeycomb and screens. Wall and floor fairings are needed to provide flat continuous surfaces at the flow boundaries in the conditioning tank. Our cost estimates indicate that completion of these components will require less than \$10,000.

3.1.3 Test Section

The test section is 18 ft long, 3.5 ft wide, and 2.5 ft deep. It is constructed of three modules, each 6 ft long, joined end to end. Structural support is provided at each joint, and optical access is unobstructed between these supports. The central module is constructed of a stainless steel liner-frame and acrylic windows, and the outer sections are constructed of a wood-epoxy composite. If desired in the future, these outboard test section modules may be replaced with window sections. Wood-epoxy construction was used in several of the LTWC components because of the low fabrication cost and because of its good properties for extended water submersion.

User access to the test section and model support mechanisms is provided at the front side of the test section by a 220 sq-ft elevated platform. Optical access for visualization and velocimetry is via the back and bottom sides of the test section. This may be seen in Figures 2 & 12.

A variable-height V-weir is employed at the downstream end of the test section to establish the water surface level, to gauge flow rate, and to eliminate longitudinal wave propagation in the facility. A system curve for the LTWC facility, is shown in Figure 4, for flow rates up to 2,500 gpm. At higher flow rates, air entrainment to the pump was encountered due to flow recirculation in the pump tank. We plan to eliminate this problem with a simple baffle arrangement in the pump tank.

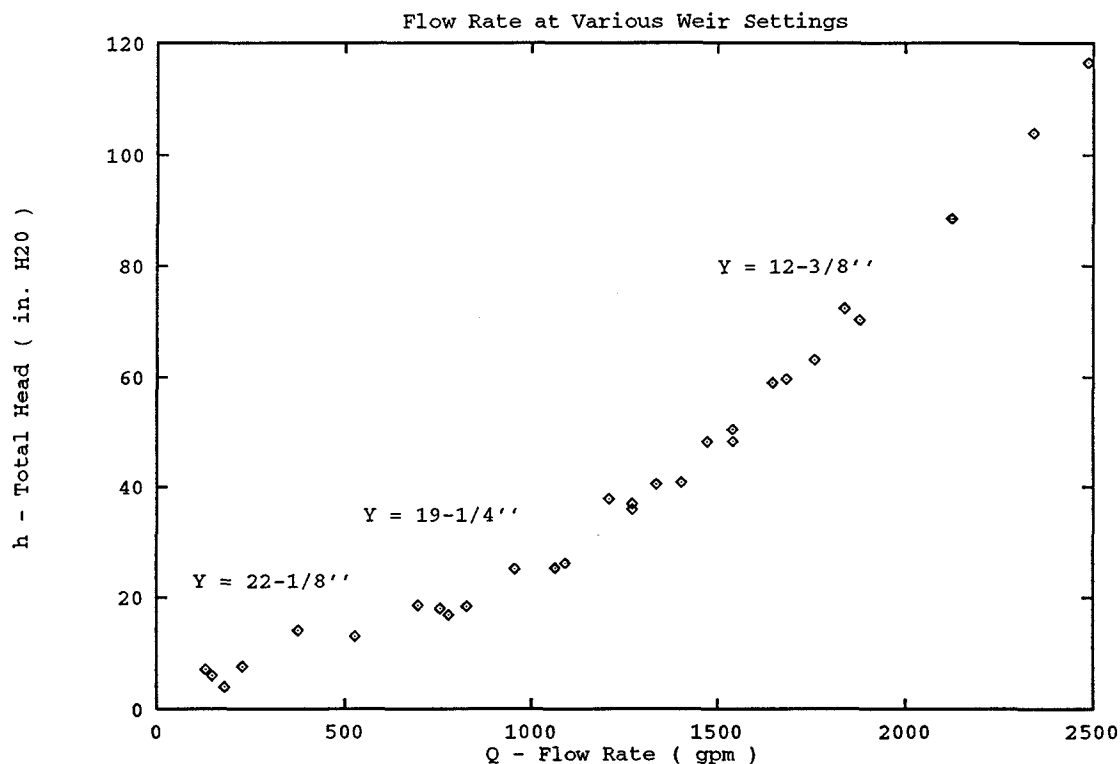


Figure 4: Weir Flow Rates

3.1.4 Pumping System

The pumping system, Figure 13, generates flow rates up to 5,000 gpm, or $U = 1.5$ ft/sec in the test section. A 12-inch axial flow pump (stainless steel) is operated at variable speed via a 25 HP AC motor and a PWM type motor drive. The axial flow pump is ideal in the high-volume low-head application shown above. It is relatively small and operates smoothly from almost zero RPM up to 1200 RPM. Since the PWM drive capacity is 50 HP, the system flow rate is currently limited only by the AC motor output. Hence, the system flow rate could be easily upgraded.

3.2 AFD Control Room

A 300 ft² control room in the AFD laboratory, see Figures 2 & 14, was built with College of Engineering renovation funds. This room provides independent HVAC for the data acquisition & control systems (DACS) and for associated instrumentation. The DACS is a MASSCOMP 5600 with 12-bit AD/DA and 16-bit digital I/O. Maximum data throughput is currently 300,000 samples/sec, with rates of 1,000,000 samples/sec possible by upgrade of an I/O card. Signal conditioning/transducer excitation is also available for strain gage and pressure transducer inputs. This system is configured for on-line data analysis, data presentation, and experiment control.

Computer Aided Design capabilities are also available in the AFD Control Room. This capability was utilized for design of the LTWC facility and components of the experimental apparatus.

3.3 Experimental Apparatus

3.3.1 Circulation Control Wing

A 20% thick elliptical wing with circulation control blowing was designed and fabricated for the demonstration control experiments. The circulation control wing components are ready for assembly and integration with the injection system. These wing components were machined at the College of Engineering Manufacturing Teaching Factory (MTF), at no cost to the project. The wing is composed of 1-thick segments, assembled to form a wing of 37-inch span.

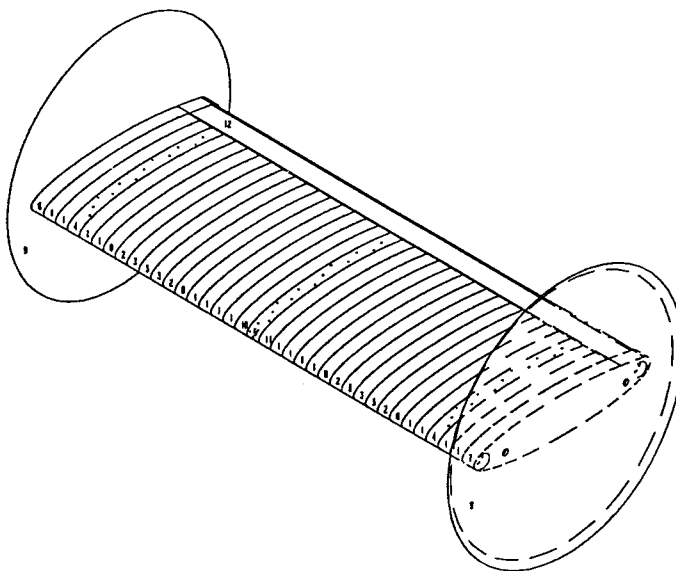


Figure 5: Circulation Control Wing

3.3.2 Injection Subsystem

A pumping system with closed-loop digital control is operational. The system, Figure 6, provides filtered flow with variable flow rate up to 32 gpm. A venturi nozzle meters this primary flow, providing feedback via pressure transducer to the data acquisition/control system. Primary flow is then throttled by the DACS D/A converter to a servo valve. The flow is divided into four supply lines which are individually balanced and metered by venturi and manometer. Integration of the Injection Subsystem to the hierarchical control system is discussed in Section 4.2.1

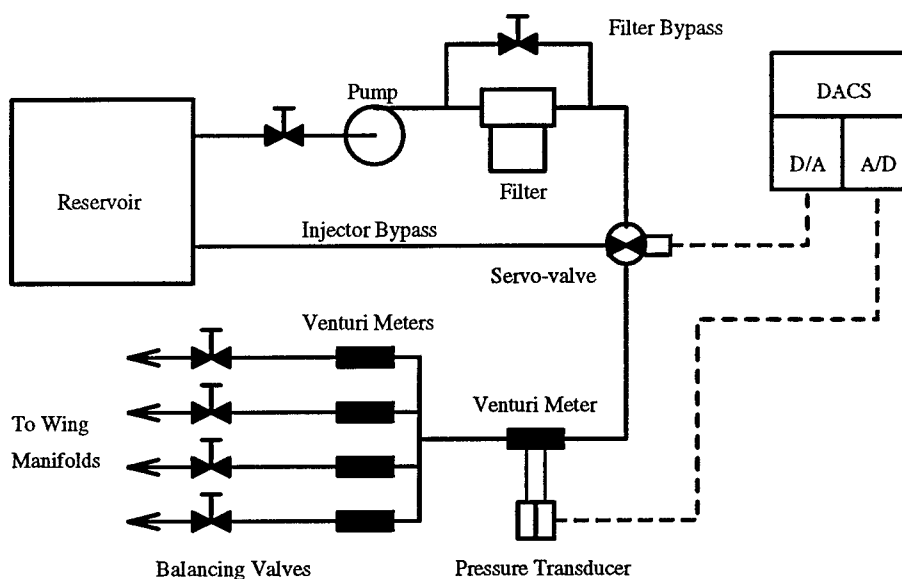


Figure 6: Injection System

3.3.3 Angle-of-Attack Subsystem

Test articles are supported by a servo-positioned traversing mechanism mounted atop the test section. A support strut extends from the traverse mechanism through the open water surface, Figure 7. In addition to supporting the wing, the support strut carries injection flow to the wing and pressure tubing back from the wing. Two types of traverse motions are currently possible with the angle-of-attack subsystem: a) streamwise translation, or b) pitching of the model about a spanwise axis. Pitching motion is accomplished by a chain drive internal to the traverse-mounted support strut. This motion is driven by a servo motor and controlled by a two-axis digital controller card in the MASSCOMP. This controller has camming and gearing capability for coordination of two axes of motion. The traversing mechanism design is described in more detail in the Senior Design Project of Gardner et. al. [11].

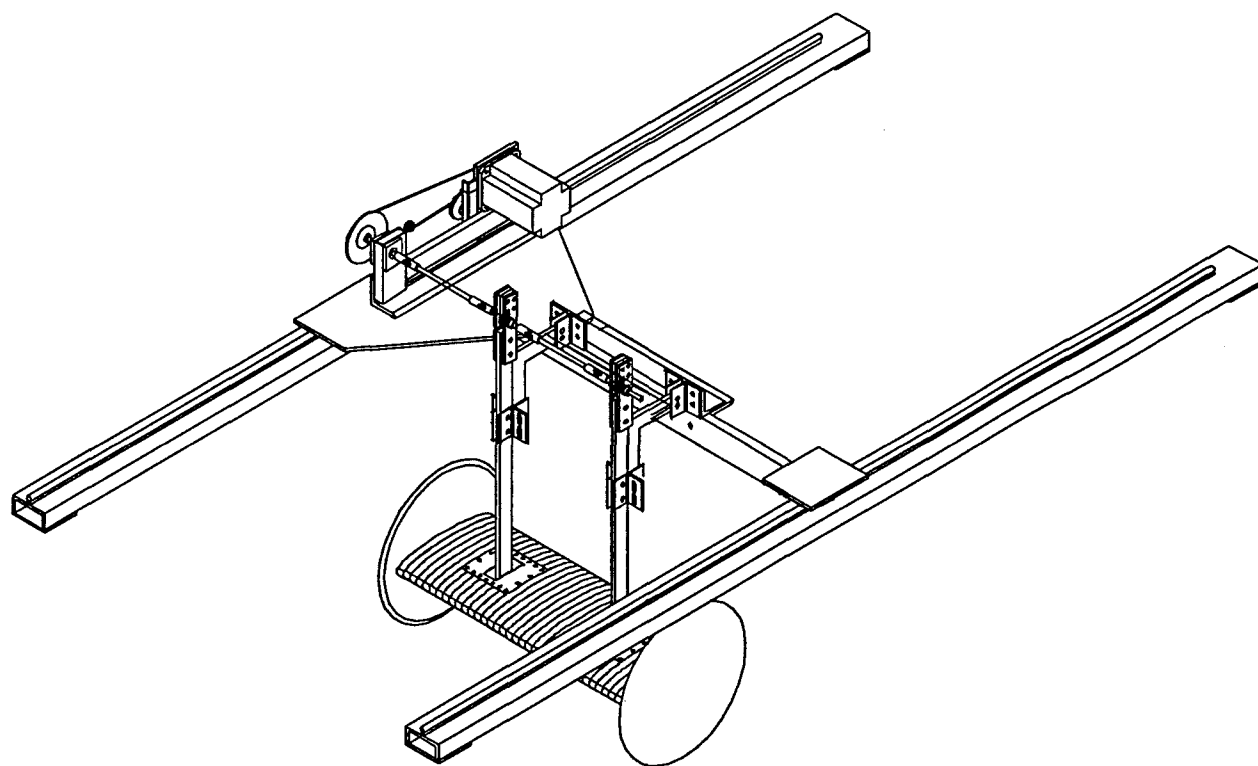


Figure 7: Model Support Traverse Mechanism

3.3.4 Load Balance

Aerodynamic lift is a primary feedback parameter to the hierarchical flow-field controller. A 3-component load balance, Figure 8, was designed by Meier [1] as a MS Project. Two of these balances were machined at the College of Engineering Manufacturing Teaching Factory at no cost to the project. Each load balance utilizes a 4-element strain-gage bridge in each component direction to maximize temperature compensation and load sensitivity. The measurement ranges are: lift (5 lb max), drag (1 lb max), side force (0.1 lb max). These balances are integrated into the Model Traversing Mechanism, Figure 7, so that dynamic loads can be taken while the model is being pitched or translated.

A calibration stand was also developed as shown in Figure 14. Software for determination of the calibration matrix and for application of the calibration for load measurement in the LTWC was completed through a Crimson-Scholar Senior Project by Jernigan [3].

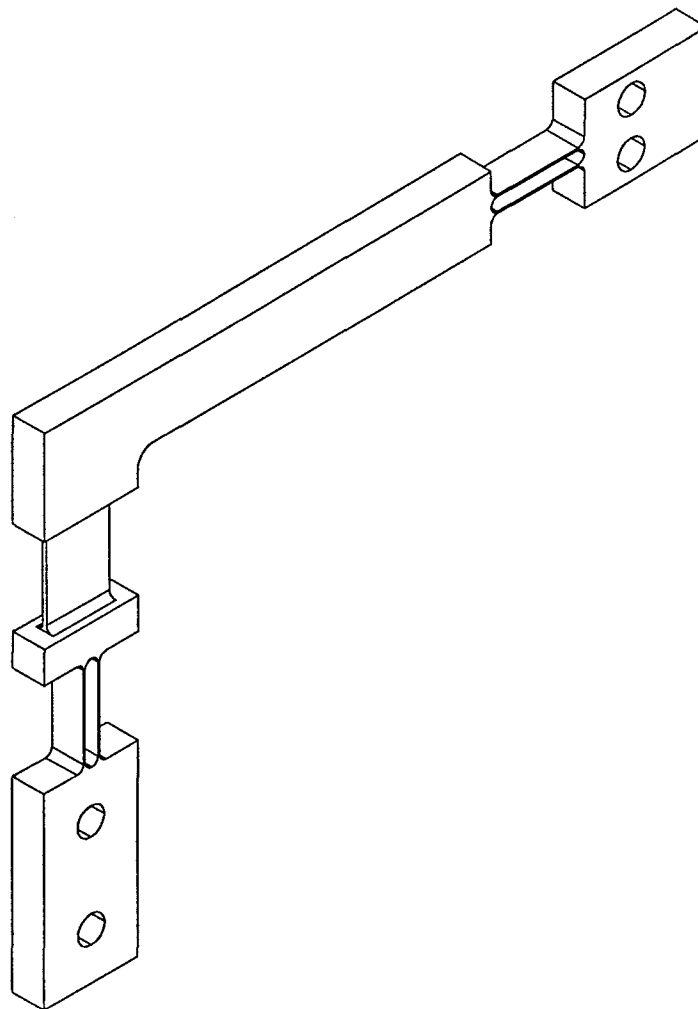


Figure 8: Three-Component Load Balance

3.3.5 Flow Visualization

Dye injection and hydrogen bubble visualization techniques were developed in the AFD Laboratory. A hydrogen bubble visualization capability was developed through an undergraduate Senior Research Project by Hunter [4]. This capability allows operation in a continuous generation mode to form streaklines, or in a pulsed generation mode to generate time-streak markers, Figure 15. A solid-state switching circuit was employed to accomplish a clean switching as governed by the input waveform from a function generator.

A laser light-sheet visualization system was also developed. This system is a two-axis laser scanner which employs a mirror-galvanometer with feedback controller for each scanning component. The system can be driven by a function generator or by the DACS D/A. The two-axis scanner provides single or multiple planes of illumination with the desired orientation. The design and assembly of the optical and electronic components for this capability was accomplished through an undergraduate Crimson-Scholar Senior project by Vanpelt [5]. This capability is complete, with the exception of the Argon-Ion laser light source.

Photographic capabilities developed for the AFD laboratory include high-resolution 120-format (6x7 cm) camera, and black-and-white darkroom facilities for developing and printing.

4 Hierarchical Control System

4.1 Flow-Field Modeling

A hierarchical control system with several levels of sophistication of automatic control was developed. A switching parameter is used to decide when a simple control scheme is insufficient, then effecting a move to the next higher level of control. We developed three models, each with an increasing degree of sophistication.

4.1.1 Model One: Attached Flow - α Control

In the lowest level control scheme, we use a rule-based compensator, such as the proportional-integral (PI) controller illustrated in Figure 9. In the traditional PI controller, we compare the desired lift vs. time profile, $R(t)$, with the measured value, $B(t)$. The difference between $R(t)$ and $B(t)$ is denoted the actuating error, $E(t)$. The angle of attack, α , is adjusted proportional to $E(t)$, in accordance with the PI rule.

While this control approach is powerful, it does suffer from several limitations. The simple PI controller cannot be expected to compensate highly nonlinear systems experiencing large perturbations. On the other hand, it performs very well for small perturbations and is extremely easy to implement.

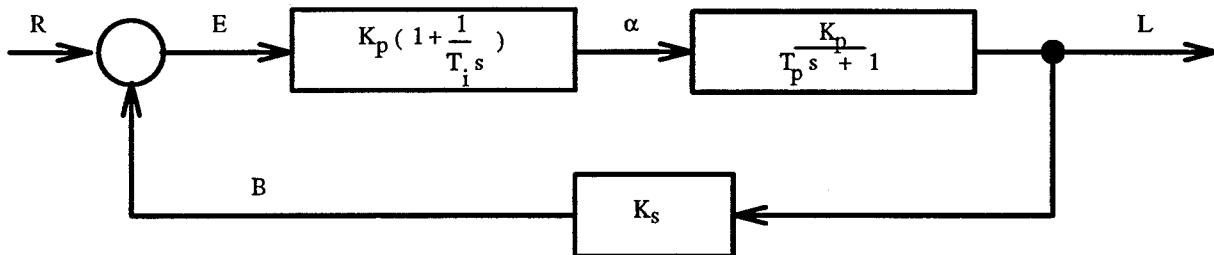


Figure 9: Proportional-Integral (PI) Controller

4.1.2 Model Two: Attached Flow - α , C_μ Control

When PI control does not provide satisfactory response to commands, the supervisory control module enforces a switch to the next level of sophistication in the control algorithm, and introduces the use of trailing edge blowing to achieve circulation control. We have obtained experimental data from Kind & Maull [2] for C_l vs. C_μ at various α . We used his data to establish a model of the form

$$C_l = K_1 C_\mu^{K_2} + K_3 \alpha + K_4$$

where the empirical constants K_1, K_2, K_3, K_4 were determined from a least squares analysis of Kind's data.

$$\begin{aligned} K_1 &= 8.88931 \\ K_2 &= 0.62436 \\ K_3 &= 0.07501 \\ K_4 &= -0.08808 \end{aligned} \tag{1}$$

A comparison between Kind's experimental data and our empirical model is presented in Figure 10. This simple model works quite well within the operational envelope of the

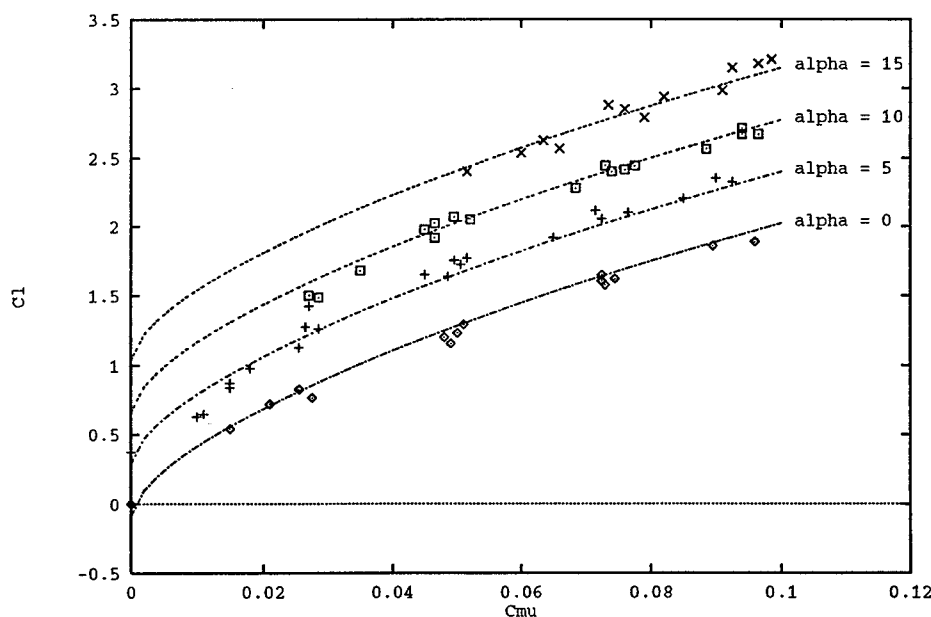


Figure 10: Model Two Using Data of Kind(1968)

wing, but cannot indicate to the controller when the operational limits are exceeded. We expect that Model 2 will give us good control performance with minimal computational effort as long as we do not drive the system near its operational limits.

4.1.3 Model Three: Attached/Separated Flow - α , C_μ Control

Our goal with the third level model is to describe the relationship between C_l , C_μ , and α which allows us to incorporate information about the operational limits of the system. For prediction of flow separation, the third model combines a Smith-Hess panel method with Head's integral boundary-layer method. This approach gives us favorable results for stall prediction as shown in Figure 11.

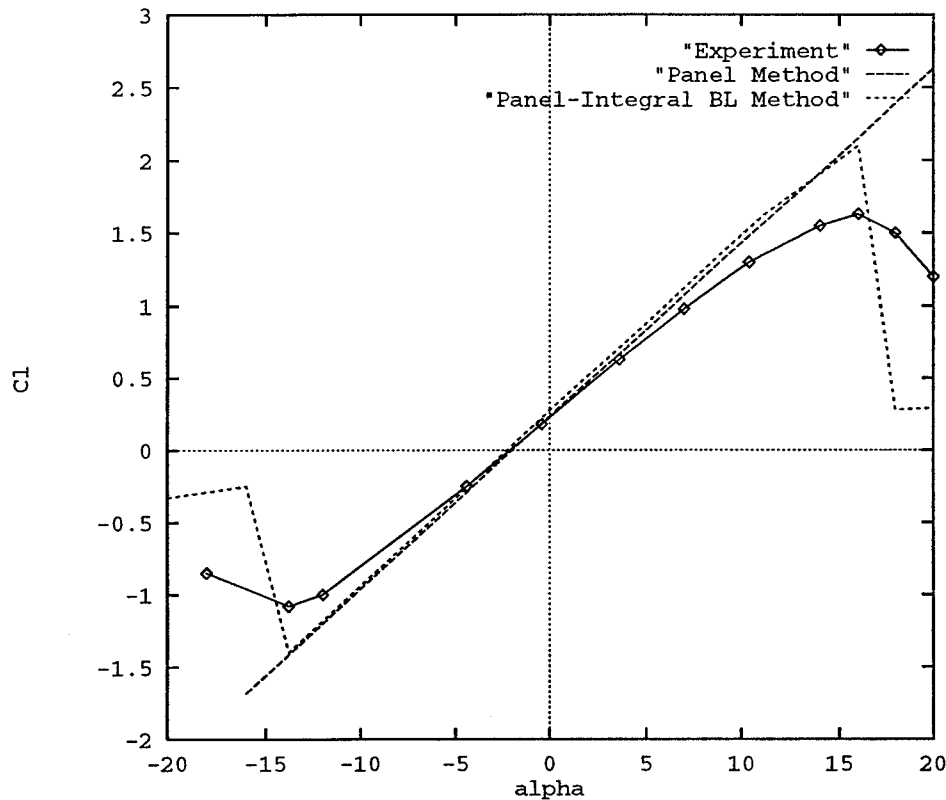


Figure 11: Model Three Using Integral Boundary Layer Method

For the case of circulation control with blowing, we have reviewed the literature to locate similar inviscid/integral boundary-layer models. We contacted R.J. Kind who provided us with source code and data for his model. Kind's model provides good predictions of lift as a function of α and C_μ , but relies on several empirical constants to establish initial velocity profiles at the blowing slot. Further implementation of this model will require development of a set of empirical constants for our wing design.

4.2 Model Implementation

Controller development was carried out for the flow injection subsystem, and for the angle-of-attack subsystem. These controllers were developed for the standalone subsystems, since the LTWC facility was not complete at the time.

4.2.1 Injection Subsystem Controller

A hierarchical controller was completed, and is now operational, for the injection subsystem. Using a simulated system response (C_l vs. C_μ) in the form of software subroutines, we have achieved injection control in a command-following mode. We have also verified the ability of the injection loop controller to manipulate the hardware in response to simulated flow disturbances by adjusting the voltage from flow metering devices. We feel confident that the injection system will perform well with traditional Proportional and PID controllers in the quasi-static performance envelope, and will be capable of following commands such as step responses and sinusoids. As expected, a type-0 control system has proven incapable of following ramp inputs, so we employed pole placement techniques to develop a higher order, yet traditional, controller. This controller was able to follow a wider range of command inputs, including ramp inputs.

Using Kind's experimental data for a circulation control airfoil in a lookup table, we next attempted to simulate injection control as the wing approaches trailing edge separation. As expected, the traditional control algorithms do not perform well in this fluid dynamic regime. The next controller in our hierarchy employs a prediction of trailing-edge separation based on integral boundary layer calculations. Separation data are computed off-line and stored in look-up table form for real-time controller access.

4.2.2 Angle-of-Attack Subsystem Controller

Our controller subsystem for angle-of-attack control is not yet operational. We have confirmed the forward and reverse operating speed control of the servomotor subsystem in an open-loop analog control mode. Closed loop control is not operational and will require implementation of the Creonics servo controller in the DACS. A device driver for the Creonics controller has been written, but still requires configuration validation for our position and rate control applications.

5 Summary

While our overall objective for a demonstration experiment was not attained, a number of valuable capabilities were developed. The Low Turbulence Water Channel Facility is operational and has demonstrated excellent operational characteristics beyond the initial design objectives. We are working on completion of the flow conditioning components for this facility, which we expect will require less than \$10,000 for materials and installation.

A range of laboratory tools were also developed to support research in the water channel facility. We also developed the key control capabilities for our demonstration experiment. Beyond our goal of a demonstration experiment, this ONR grant has provided educational support for many students. This has resulted in 2 Masters Thesis', 1 Masters Project, and 6 undergraduate research reports.

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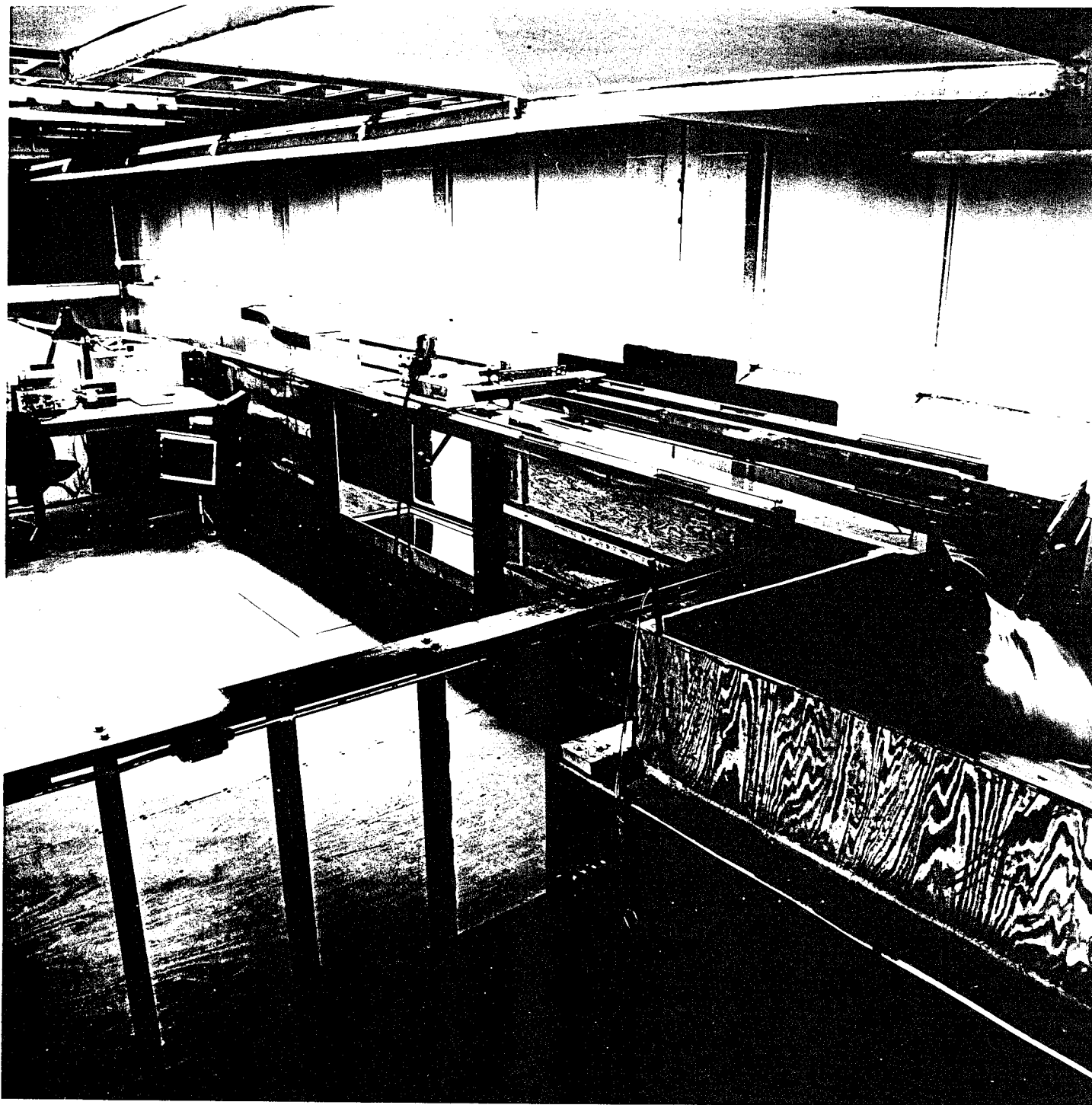


Figure 12: The LTWC facility. Flow passes from the flow-conditioning tank (13,000 gal in the background, through the contraction fairing and into the test section in the foreground. Test articles are supported by the traversing mechanism on top of the test section.

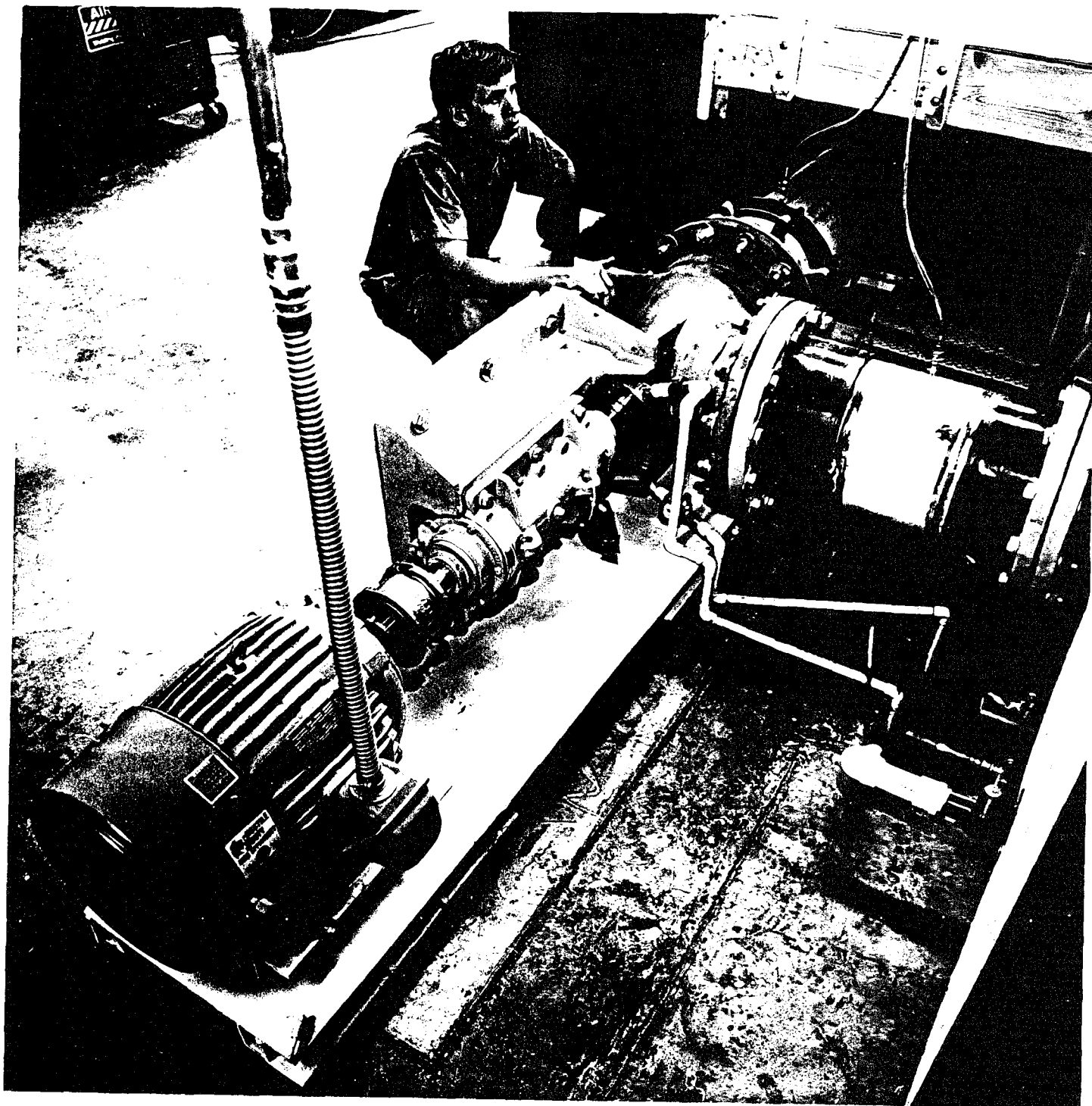


Figure 13: The LTWC Pumping System. This is a Gould stainless steel SEAF 12-inch axial flow pump, coupled to a 25 hp AC motor and driven at variable speed by a Toshiba 50 hp PWM drive. As currently configured in the LTWC, we flow 5,000 gpm at 25 hp. The pump can supply up to 7,000 gpm with upgrade to a 40 hp motor.



Figure 14: The AFD Computer Room. This provides environmental control for the data acquisition and signal conditioning systems. Here, the load balance is being calibrated before installation in the LTWC facility.

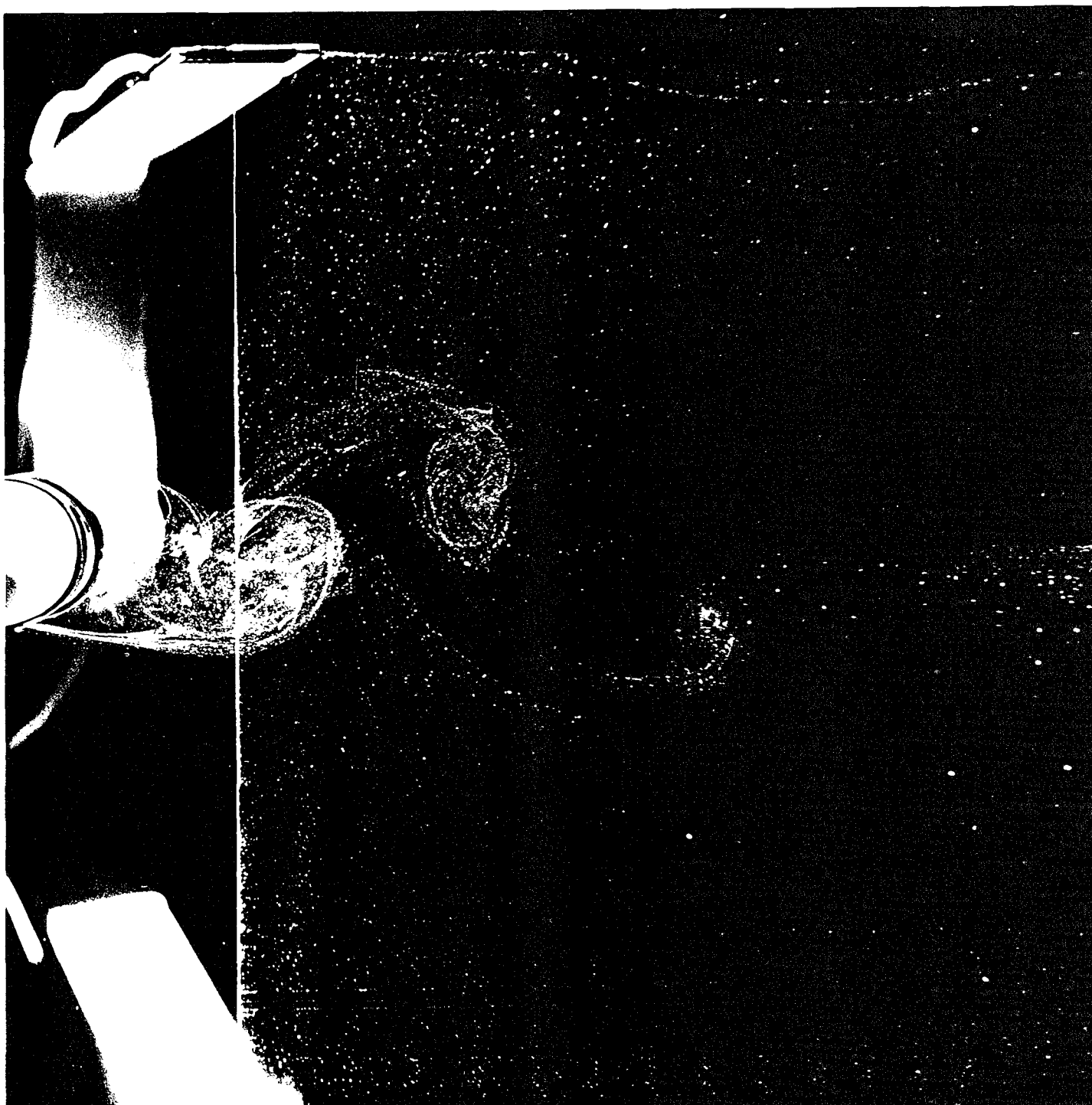


Figure 15: Hydrogen-Bubble Visualization. This is the first visualization done in the LTWC. Flow is from left to right, past a circular cylinder at $U = 0.32$ ft/sec, $R = 2,000$. Two wires, parallel to the cylinder, are operating continuously. One wire, normal to the cylinder and in its wake, is being pulsed at $n = 7.4$ Hz. The visualization confirms a Strouhal number of $S = nd/U = 0.20$.